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PURSUING MECHANICAL PART FEATURE RECOGNITION THROUGH THE ISOLATION OF 3D FEATURES IN ORGANIC SHAPES

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ABSTRACT

The successful extraction of 3D features in mechanical parts has always been a challenging task and has yielded mixed results. Extracting features from organic shapes however is even more difficult. This is due to the fact that they are defined by both gradual and abrupt changes in surface curvature. The term curvature is explained in detail in section 4. Learning how to recognize organic shapes may give insights into better ways of performing feature recognition on mechanical parts. Determining the exact values of curvature, based on the underlying parameters can prove to be quite difficult. Curvature can be a good tool to identify features as most of the features are areas of slowly changing curvature bounded by sudden changes in curvature. The benefits of developing a generic algorithm that picks out curvature, and hence the organic features, are quite huge.

This paper explains one approach taken to accomplish this task. This paper studies characteristics of the watershed algorithm[1] when applied to the features on bones. This algorithm is used to isolate features based on curvature gradients. This paper uses the knowledge from the field of anthropology and medicine to explore the sensitivity factor analysis of the watershed and its effectiveness in extracting the features on bones. The paper also compares the differences between the anatomists definition of a feature and the algorithm interpretation of the same feature.

INTRODUCTION

Feature recognition from 3D models has been a goal for engineering design and manufacturing for more than 25 years, ever since computer-aided design tools became available. The purpose of recognizing and classifying geometric features in engineering parts is essentially to raise the semantic knowledge for a discrete part or assembly. For example, recognizing holes in one object and pins in another and establishing that the hole and pin patterns are congruent gives knowledge that the parts fit together. In a manufacturing sense, recognizing pockets, slots and holes in a component implies specific manufacturing

processes and allows software to perform manufacturing process planning automatically. In general, features are patterns and patterns have significance in form, fit and function. Being able to search for and classify features enables better and more pervasive CAD/CAM success. Possibly the highest leverage application of features today is in design reuse. Searching for and retrieving a design similar in features or shape to a desired, but not produced part can allow a designer to borrow other parts or portions of parts for new designs and reduce the design time and time to market. Design reuse is an important research topic today [2].

Although computerized feature recognition seems important, the success rate over the past 20 years has been mixed. Most efforts concentrate on holes, slots, pockets and other patterns, which typically are prismatic in nature. Our feeling is that feature recognition progress will be accelerated if researchers “back up” a bit and ponder insights gained from looking at nature’s shapes, i.e. organic shapes. Organic shapes do not conform to manufactured feature shapes with sharp edges and obvious boundaries. In fact, organic shape recognition and classification deals with fuzzy feature boundaries and imprecise definitions. If we can solve feature classification of organic shapes, which are fuzzy, then our contention is that we may be able to apply those techniques more accurately to product features. It is obvious that organic shape recognition is possible because humans recognize and classify the features of acquaintances in everyday life.

As a “divide and conquer” step in this shape recognition research, we define the task as subdividing an object into identifiable or at least less complex regions. This paper deals with the isolation of feature regions in preparation for classification of each region and finally topologically recognizing and classifying the resulting graph of regions on the 3D object.

1. HUNTING FOR FEATURES

The feature hunt is essentially the sequential breaking up of the 3D object into patches and then using curvature descriptions to match the characteristic features. This method of approach has been employed to the femur in this paper. The progressive breakdown was done using the watershed and then the features obtained were compared with the anatomical features defined in the next section. Various steps are used to follow this process of subdivision. The three steps including subdivision have been explained below.

Subdivision

This section has been explained above. This involves the splitting up of a single object into the required features.

Definition of Search pattern

This process defines the search pattern, which is the equivalent of the key word in normal searches. This is done by picking a feature of interest and using it as a primary object for the search. Work on the definition of the search pattern is continuing at present and will be the subject of subsequent papers. The search pattern is divided into a triangulation mesh to analyze the shape and curvature details of the feature.

Searching Databases

When the search engine is complete, the feature, in the form of a standard pattern definition will be used to search existing digital databases. The program will identify features that have similar parameters.

2. ANATOMICAL ASPECTS

A cow femur was used to test the threshold values of the watershed algorithm on feature isolation. We will discuss the main anatomical features on the cow femur from the anatomists' point of view (Appendix I). This will help establish a frame of comparison between the output of the watershed and the actual feature. The features have been explained one at a time.

Figures A2.1 and A2.2 show the similarities and differences in various femurs.

The cow femur was picked because it was readily available to the authors. Once the analysis is done on the cow femur the idea is to extend it to the human femur and other bones.

FEMUR

The femur is the most proximal bone of the hind limb. It is the longest and the strongest bone in most mammals. It has a cylindrical profile in the greater part of its extent. In humans it is not entirely vertical when in the erect posture. It is inclined downward and medialward from the hip to the knee. Two main divisions can be made on this bone that is the body and the two extremities. This discussion will help with the explanation of the feature isolation table in Appendix II. The main features have been listed below.

i) Upper Extremity – Head, Neck, Greater and Lesser Trochanter.

ii) The lower Extremity – Patellar surface, Intercondyloid Fossa, Medial and Lateral condyle.

The tree diagram (in Appendix I) shows all features on the human femur. Some of the common features have been discussed in detail.

Major and Minor trochanters are connected by the trochanteric crest behind which there is often a deep *trochanteric fossa* (a depression or a pit). A broad articular area is present at the distal end where the femur swells out. The proximal-distal groove present on the lower part of the bone accommodates the patella (kneecap). This is flanked by two more of the features the *medial* and *lateral condyles* that form joints with the condyles of the tibia. In between the condyles is the deep *intercondylar fossa* and on either side of them are moderately prominent tuberosities (a rounded bulging feature where a muscle or a ligament attaches to the bone), the medial epicondyle and the lateral epicondyle.

Body

The body is mostly cylindrical with a lot of tuberosities and fossae. These are parts where the muscles of the leg attach onto the bone. One the more prominent feature is the *supracondyloid fossa*.

Head, Neck & Fovea

The *head* bears, on its medial side, a prominent fossa called fovea capitus. The fovea is an isolated pit in humans and cows.

The head (figure A2.3) is prominently ball-like and bulging out of the *neck* on all sides in humans. In the case of cows, the head does not bulge out of the neck because the neck gradually moves on until it meets the border of the head. In the proximal side, the neck gradually widens onto the head thus utilizing more of the neck.

Trochanters

The *major trochanter* tapers into the small but distinct *minor trochanter* in cows. The curved ridge that connects the two trochanters is called the trochanteric ridge. There is a similar ridge in humans as well that link the two trochanters. The minor trochanter is small but prominent in humans as well.

Patellar Area

The patellar area, with a broad and shallow groove running along a distal proximal line; the medial and lateral borders branch out of this area to maintain a broad contact with the condyles; the patellar area is relatively symmetrical but the lateral border is more prominent than the medial border due to a bulge.

Condyles & Supracondyloid Fossa

The condyles (figure A2.4) are the features that attach onto the matching features in the tibia. The *Lateral and Medial condyles* are the two condyles.

The lateral *supracondyloid fossa*, a rough depression to proximal of the lateral condyle, is especially prominent and broader in cows and not prominent in humans.

These various features are present on the femur. They have been dealt with one-by-one later in this paper.

3. SEGMENTATION

Isolation of features begins with a triangulated surface model of an object. Triangular facets are used because of their planar properties, ease of computation and routine availability. For example, the STL file format represents solid objects as a triangulated mesh. The goal of this work is to study the segmentation of this mesh based on curvature calculations and the watershed segmentation algorithm.

Various approaches to segmentation of solid objects have been reported including the volumetric approach by Kim[6] and Woo[7], a feature based approach by Razdan ([8],[9]) and a viewpoint based method by Gadh ([10],[11],[12]).

Another approach that was described by Sonthi et al. [13] classified a 3D surface into three broad classes of protrusions, depressions or flat regions. These regions could not be easily represented using polygonal meshes. The representation of curvature is thus quite difficult. This method of polygonal meshes has replaced by the watershed method.

4. MEASURING CURVATURE

The watershed is greatly dependent on the accuracy of the curvature calculation. Curvature can be defined using differential calculus in the form of single derivatives and double derivatives. The following reference material was the source for all the arithmetic discussion done below. Besl[14], DeRose[15], Farin[16], Hyde et al.[17], Stoker[18], Stuik [19] and Willmore[20].

The parametric surfaces considered are of the form

$$x = x(u); u = (u; v) \in [a; b] \subset \mathbb{R}^2; \quad (1)$$

u and v are integer parameter values in the domain $[a, b]$. The functions $x(u; v) = (x(u; v); y(u; v); z(u; v))$ are single valued and are known to possess continuous partial derivatives.

The first fundamental form, denoted by I is given by

$$I = x' \cdot x' = Edu^2 + 2Fdudv + Gdv^2 \quad (2)$$

Where

$$E = x_u^2 = x_u \cdot x_u; F = x_u \cdot x_v; G = x_v^2 = x_v \cdot x_v;$$

The second fundamental form, denoted by II is given by

$$II = Ldu^2 + 2Mdudv + Ndv^2; \quad (4)$$

Where

$$L = Nx_{uu}; M = Nx_{uv}; N = Nx_{vv} \quad (5)$$

and N is the surface normal at point x .

The normal curvature of the surface at point x in the direction of tangent t is given by

$$\kappa_0 = \kappa_0(x; t) = \frac{II}{I} = \frac{(Lu')^2 + 2Mu'v' + (Nv')^2}{(Eu')^2 + 2Fu'v' + (Gv')^2}$$

Since the normal curvature is based on direction, it attains maximum and minimum values, called the principal curvatures. The Gaussian curvature is obtained by combining principal curvatures κ_1 and κ_2 .

$$K = \kappa_1 \kappa_2 = \frac{LN - M^2}{EG - F^2} \quad (6)$$

CURVATURE TYPES

The three main types of curvature are Mean Root Mean square and Absolute. The mathematical formulae for each of these curvatures have been listed below.

Mean Curvature:

$$H = \frac{(\kappa_1 + \kappa_2)}{2} = \frac{1}{2} \frac{NE - 2MF + LG}{EG - F^2} \quad (7)$$

Root Mean Square

$$\kappa_{rms} = \frac{\kappa_1^2 + \kappa_2^2}{2} \quad (8)$$

Absolute

$$\kappa_{abs} = |\kappa_1| + |\kappa_2| \quad (9)$$

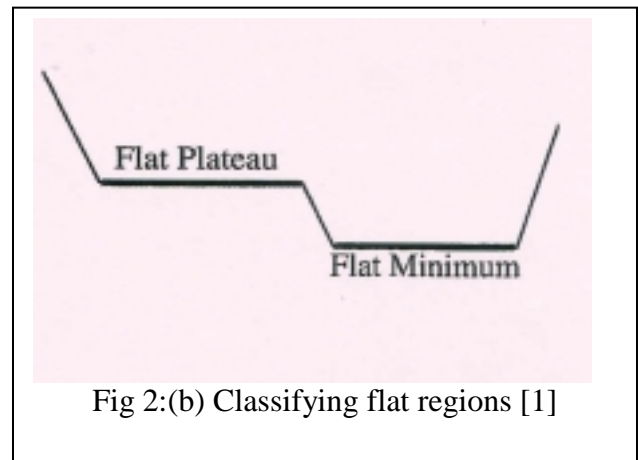
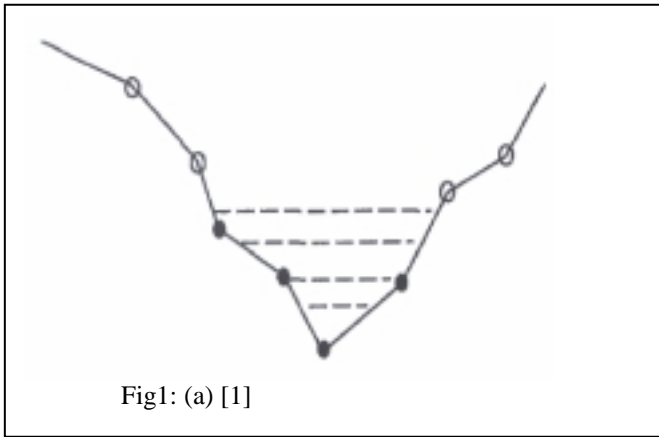
The absolute curvature is not used as much as the other two because the calculation of κ_1 and κ_2 are expensive to compute.

5. THE WATERSHED ALGORITHM

The basic watershed is done in a sequence of steps. They are based on a local search algorithm. This algorithm is designed to search for the local minimum in a particular neighborhood. There are two basic strategies to perform the watershed.

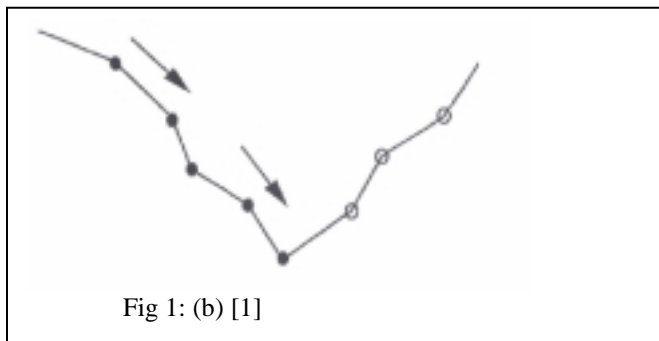
(a) The Bottom Up Approach:

The bottom approach starts at the local minimum and then incrementally floods the region until the neighboring regions connect. This helps to find the catchment basin that defines a local region. Fig1. (a)

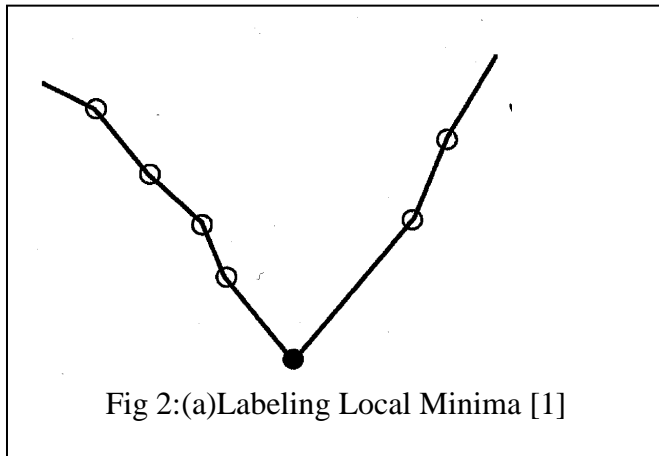


(b) The Top-Down Approach:

This approach moves a token from a local maximum to the next lower maximum until it reaches the minimum. Fig1. (b).



In a 3D mesh the position of the vertices are irrelevant, as it is only the height function that affects the formation of the catchment basins. Thus, the segmentation is affected by the shape of the surface through the height function.



Therefore the steps involved in the watershed algorithm are:

1. Computation of some height function like curvature at each vertex.
2. Evaluation of local minima and assigning each a unique label. Fig2. (a)
3. Finding each flat area and classifying it as a minimum or a plateau. Fig2. (b)
4. Looping through plateaus and allowing each one to descend until a labeled region is encountered.
5. All of the unlabeled vertices are allowed to descend and join the labeled region.
6. Regions with the watershed depth below a set threshold value are merged.

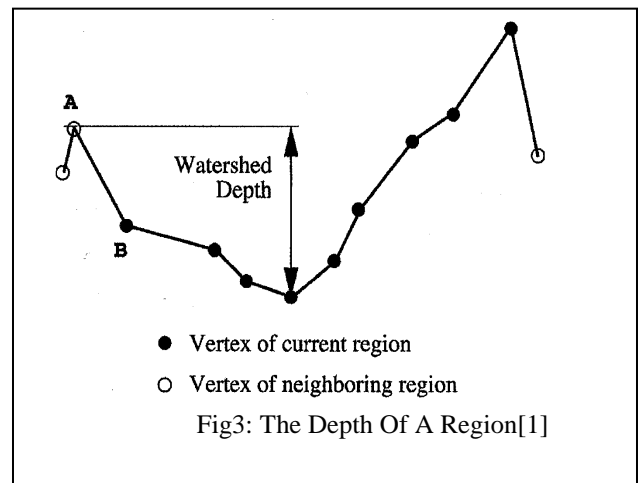


Fig. 3 shows the definition of the depth of a region as the difference between it's lowest and highest boundary vertices.

The final step in the algorithm is the merging of adjacent regions with shallow depths. This is shown in the next figure. Fig.4

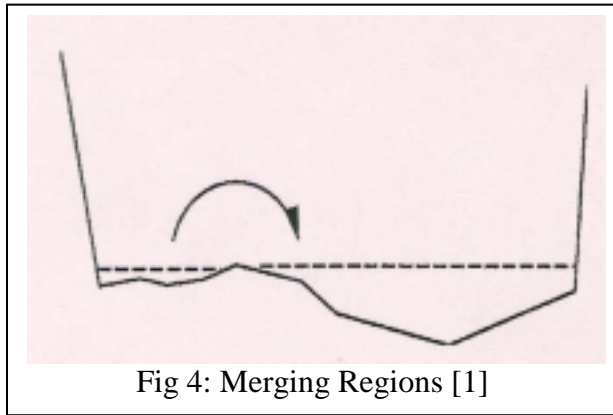


Fig 4: Merging Regions [1]

The implementation of watershed we have used is an algorithm that maps a 3D object based on curvature details. Various parameters can be required for employing this algorithm including (i) Curvature and (ii) allowable Tolerance while comparing curvature values κ for similarity.

The watershed uses the mesh generated in subdivision. In the watershed algorithm there is no redundancy of the point and at a particular point only one dataset is present. The vertices are marked v_i and each of these vertices is given a value of κ_i . This value determines the region to which the vertex belongs. The vertices with the same κ are grouped into regions separated by other vertices with different κ value. The value of κ denotes the curvature. The place where there is a change in the value of κ acts as the region boundary. The scheme for improved curvature estimation is presented in [21].

6. THE WATERSHED INTERFACE

The implementation of the watershed algorithm applied to triangulated mesh parts allows the user to open a mesh file, calculate curvatures, use the watershed algorithm to segment the surface and view the results with color coded segments. The user has control over several options, however this paper studies only the option of changing the threshold value.

illumination point sources can be used. The orientation buttons are used to

- i) Rotate about XY
- ii) Rotate about YZ or
- iii) Translate in XY

This helps the user place the object at a particular position and angle of his choice. Setting them to a uniform viewing angle for a sequence of pictures minimizes confusion and one can study or compare two similar features.

The segmentation buttons are used to gradually build the curvature map. The first button is responsible for the calculation of curvatures, which are then labeled with the region to which it belongs when the second button is pressed.

The third button descends through the object. This descending occurs as a series of steps. The calculation for curvature κ_i is done at each of the vertices in the mesh. This curvature κ_i can be any of the three types discussed previously. Once this is done, the program or the algorithm reads all the points and their respective κ values.

In this problem, we consider only the magnitude of the curvature. The magnitude determines whether it is a Convex or a Concave area. Convex areas (elevations) always have a high positive value of curvature and the concave areas (depressions) have high negative values of curvature. Two other features formed are ridges and valleys. The ridges have high positive curvature and the valleys have high negative curvature. The original watershed algorithm segmented the object based on the regions of high positive curvature and thus the valleys would not form the region of separation. However, in this study, only the magnitude of curvature is considered and both hills and valleys are segmentation boundaries.

Finally, the last button merges all the regions to show the image with various colored patches that indicate the various curvatures.

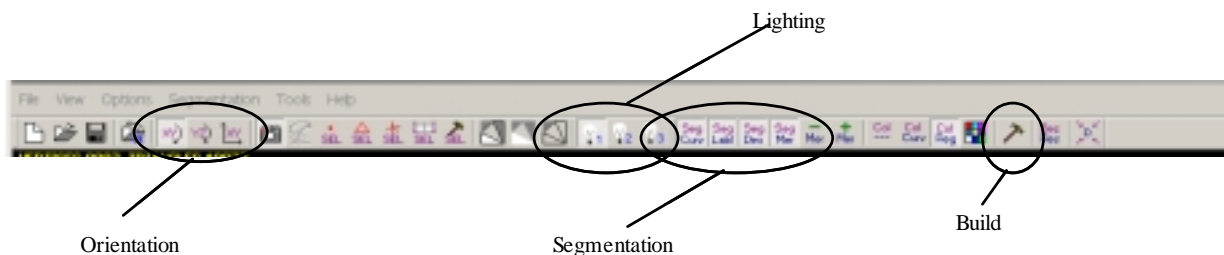


Figure 5: Menu controlling the watershed viewing and results.

Options in the main toolbar (Figure 5) can be used for better visualization of the object. The buttons and their function have been explained pictorially.

The buttons shown in the toolbar above are also used in various combinations to obtain the required visualization. Three

The merging occurs in a sequence of steps. More can be seen about the hybrid approach [4] that combines the concept of the Dihedral Angle with the technique that has been discussed above for segmentation. In this particular method, the aim is to assign triangles, not vertices, to a common region. The conditions used to merge are given below. More about the

vertex labeling and the merging can be seen in Mangan [1] and Razdan [4].

Case 1: All vertices have same label

This is the simplest case where the triangle is assigned the region number of its vertices.

Case 2: One vertex has a single label

When one vertex has a unique label and the other vertices have multiple labels, the triangle is assigned to the single label vertex.

Case 3: Multiple labels but only one common label

There are multiple labels possessed by each vertex and only one of them is common. The common label to all three vertices becomes the region label.

Case 4: All Edges are Feature Edges

The region gets qualified as a region by itself.

Feature Vertices: Feature vertices make up a feature edge which is in turn common to two feature faces.

Case 5: Multiple Labels and Multiple common Labels.

A vertex may have more than one label and more than one can be common with the other vertex. A feature edge common to two triangles is selected. Then, the common vertex labels of the targeted triangle are compared with the common vertex label(s) of the neighboring triangle. The label that does not belong to the set of common vertex label(s) of the neighboring triangle is assigned to the targeted triangle. If the targeted triangle has more than one feature edge, then the common labels for each neighboring triangle of each feature edge side using the method above are selected. Then, their common label is assigned to the region of the targeted triangle. The targeted triangle may have no feature edge. This implies that the triangle shares a common region with the neighboring triangles. Thus, the target triangle and the neighboring triangle region are taken to be the same.

This is how the merging of features occurs. It is worth noting that these patches may not have the same colors when the process is repeated. In addition, the curvatures calculated will change shape and size with a different parameter value. This is explained as the function of the Build button.

The button 'Build' is used to perform the curvature mapping. This mapping is again done based on the height function or the curvature function κ . The options setting window (Figure 6) appears when this button is pressed. This window is used to change the sensitivity of the curvature mapping. The main control on this window is the Threshold Value. The analysis in this paper revolves around the effect of that particular parameter on the feature extraction.

Thus, this parameter determines how the curvature map looks. A diverse range of curvature maps result from a small change in the threshold value. The table (Appendix III) discussed in this paper deals with the effect of threshold value on the curvature map in the watershed. It also discusses the potential of the watershed to isolate features specified by the anatomists.

7. SCANNING OF OBJECT

A cow femur was scanned for the purpose of this analysis using a Cyberware Model 15 scanner¹.

The laser scanning equipment was used to pick up data points from the surface of the object at a density of 100 points per inch in both lateral and longitudinal surface coordinates. A series of scans was done to obtain as many of the parts of the bone as possible. These scans were then merged to obtain the final data set. Because of the unnecessarily dense points in these scans, the point data was filtered to generate a maximum of 20,000 triangles.

After scanning, the model was decimated using Geomagic Studio². This new file is opened in the watershed software. Curvatures were calculated and the watershed algorithm was executed using an array of threshold values. The threshold value has high sensitivity (isolates many small patches) when low and low sensitivity (generates fewer and larger patches) when high. The number of colored patches or the number of curvatures detected determines the sensitivity. The threshold value can be simply explained as the curvature measuring parameter.

This study has experimented with values of the threshold value. The main results are shown in Appendix III. There are four main columns:

- Feature Name
- Threshold Value
- Image of results
- Comments.

The last of the columns explain the efficiency of the watershed to highlight the exactly same features as defined by the

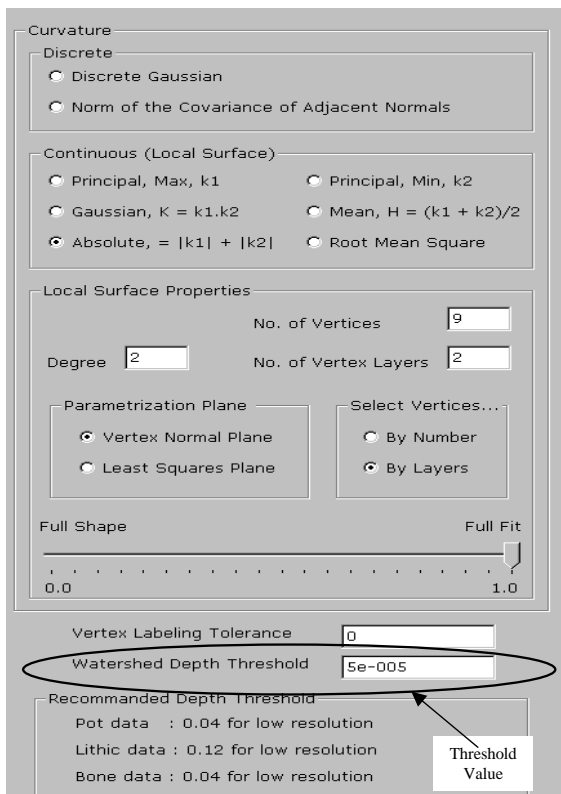


Figure 6: Setting the Watershed Threshold

¹ Cyberware, Inc., Monterey, CA

² Raindrop Geomagic, Inc., Research Triangle Park, N.C.

anatomists. It is hoped that the reader will be able to detect in these pictures of isolated patches, that the watershed algorithm when applied to this bone can, in fact, isolate individual features that have meaning to anatomists. Furthermore, it can be seen that setting the threshold can be difficult. It is our plan to develop a guide to the user and some automated isolation methods to improve or possibly automate feature isolation in bones.

8. CORRELATION BETWEEN ACTUAL AND EXTRACTED FEATURE

The correlation between the actual features on the bone and the features that were extracted using watershed have already been partly discussed at least qualitatively, in the tabular column (Appendix III). The comments column in the tabular column takes the feature and explains how that particular feature has been split up or identified by watershed. The range specified is the range in which the curvature mapping of that particular feature does not change. The table represents the closest result to the actual feature identified by anatomists.

There are a few complications due to the watershed as it is incapable of exactly picking out all features exactly. The output of the watershed is very unpredictable. There is no way that even an expert can predict the exact threshold value for a feature. This is the biggest disadvantage of Watershed.

9. CONCLUSIONS & SUGGESTIONS

- The main drawback of this process to date is that the scanned object must be decimated, as in the number of triangles have to be reduced for the algorithm to work. This may result in the loss of important curvature data granularity.
- A change in curvature was detected whenever there was an inflection in the surface contour.
- Some features were more easily picked up than others.
- It was noticed that a feature in the form of a large depression was highlighted over a larger range of threshold values. The exact range of threshold values for a particular feature cannot be easily pre-determined even after working with watershed. Although the range can be predicted for similar features on two similar types of objects, e.g. one can predict the range of values in which the head is picked up on two separate femurs.

It has been assumed that a suitable number of significant digits for the threshold value are five. This could change for some features where there is a change in the curvature mapping at the sixth decimal point and, on the other hand, some features may not be significantly affected after the 3rd decimal place itself.

Further work will hopefully show a relationship between the threshold and a predictive method for finding suitable threshold values for specific feature types.

ACKNOWLEDGMENTS

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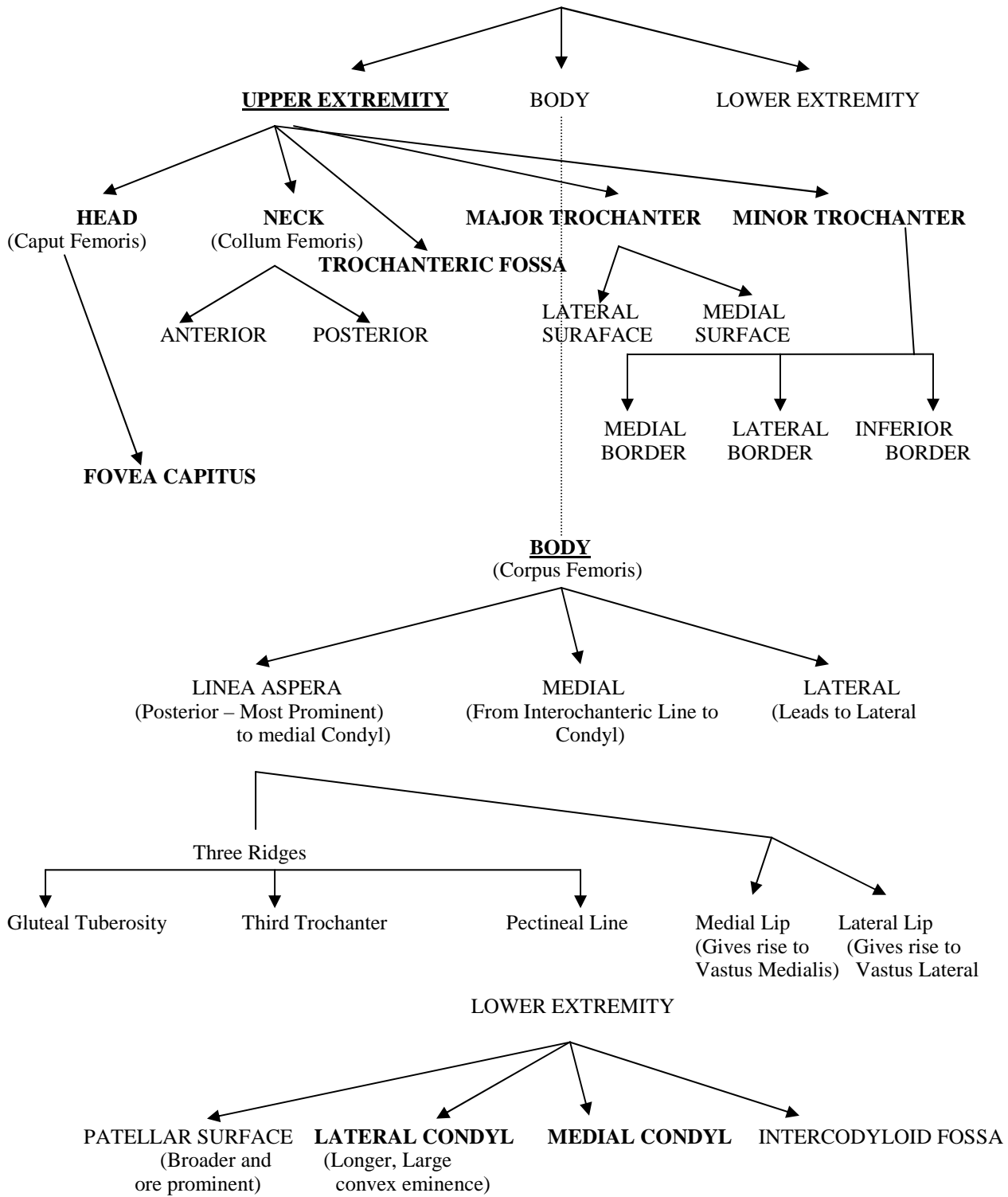
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APPENDIX I

FEMUR (TREE DIAGRAM)



APPENDIX II

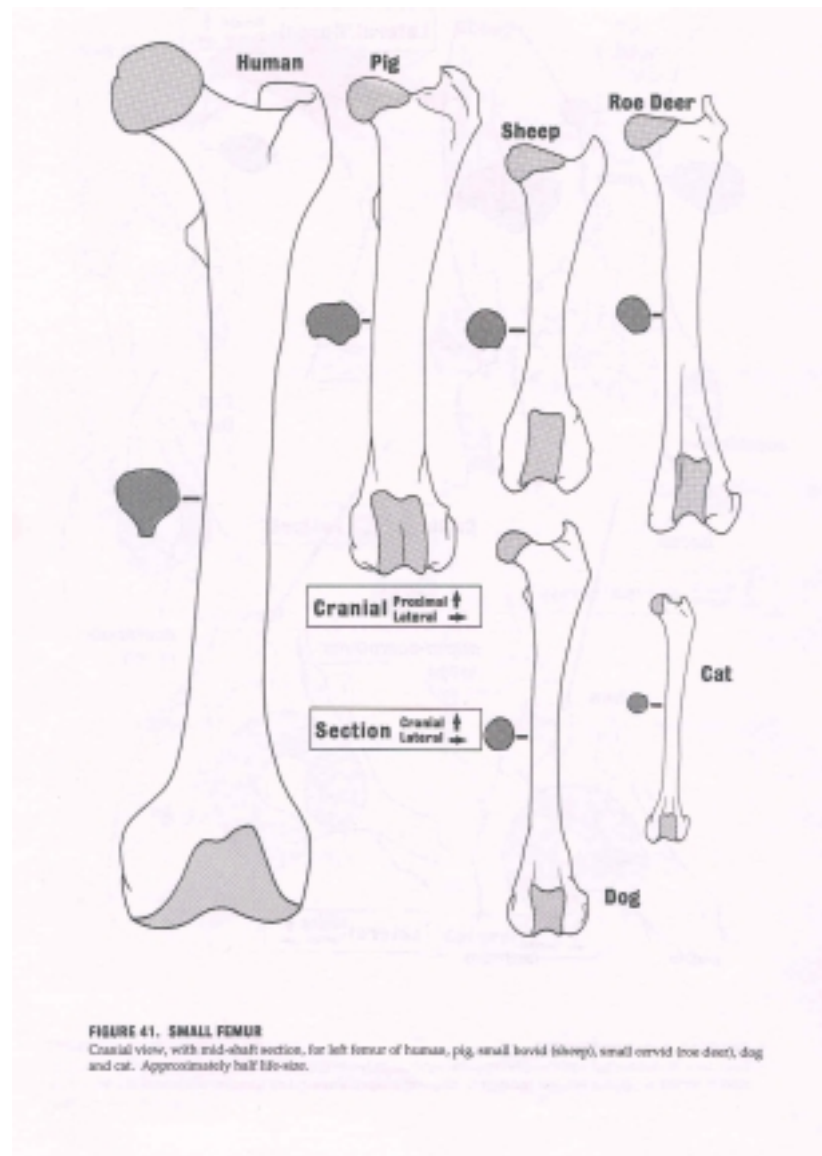


Figure A2.1: Anatomical features on a femur, cranial view [3]

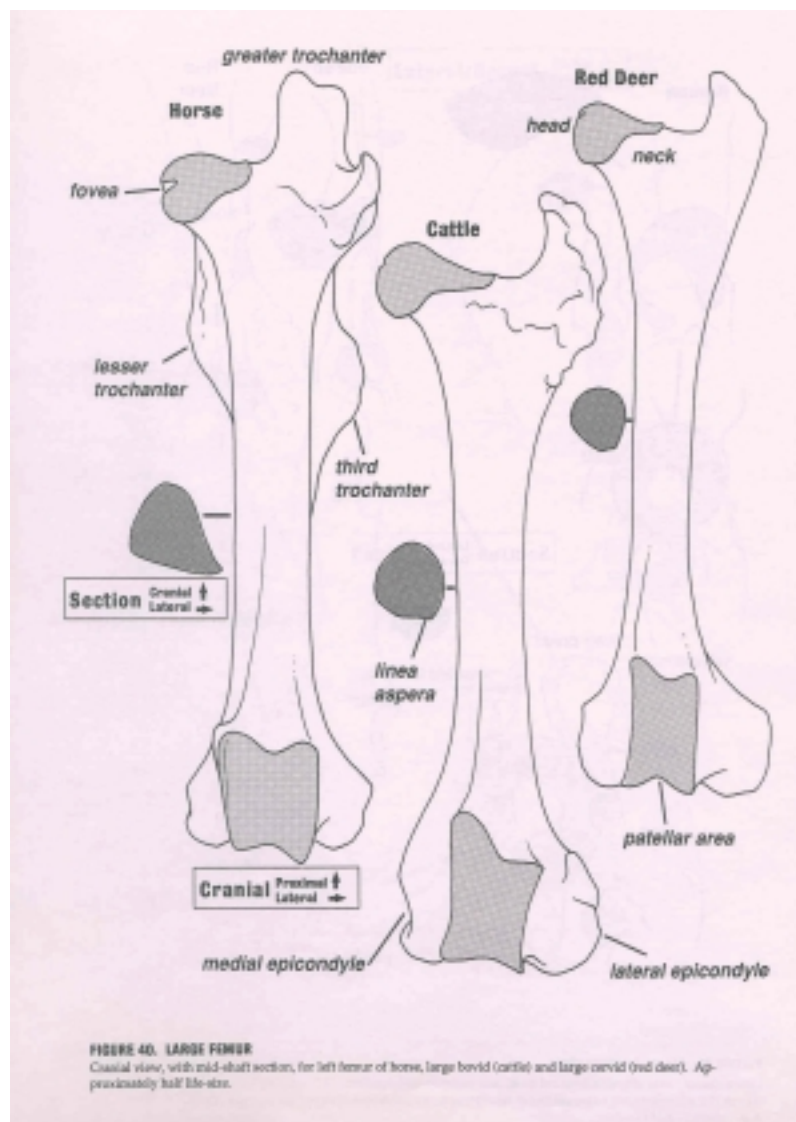


Figure A2.2: Caudal view of the cow femur [3]

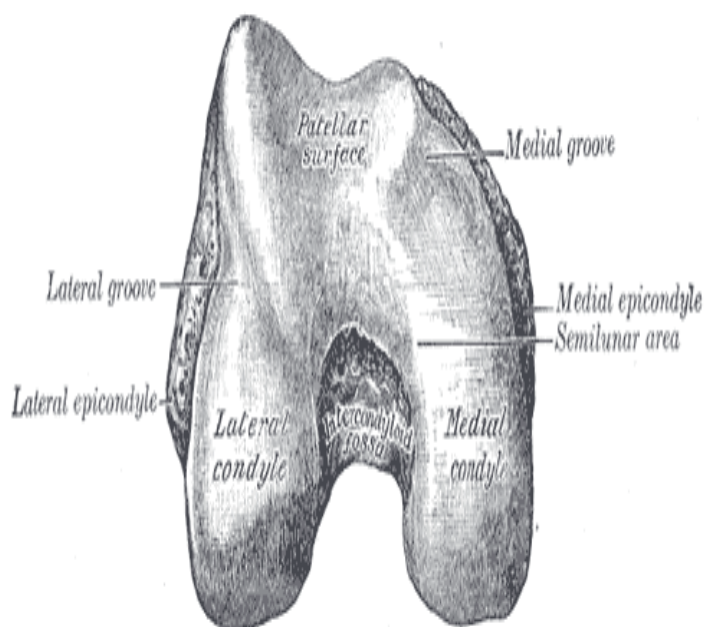


Figure A2.3: Condyles [22]

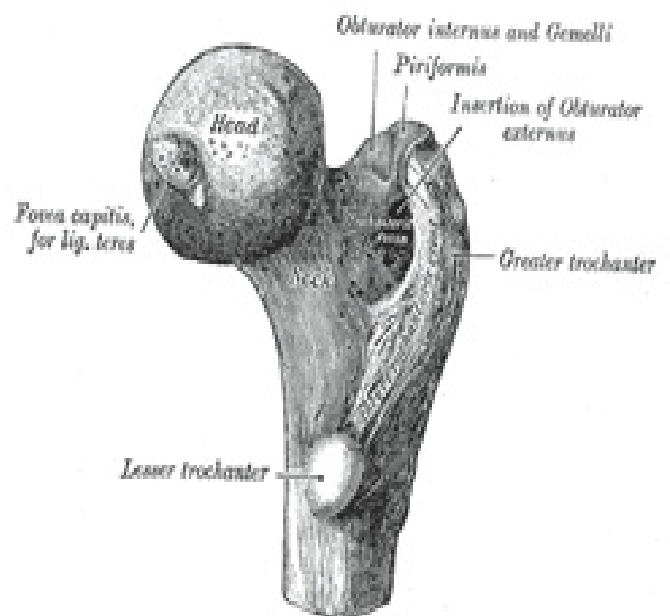
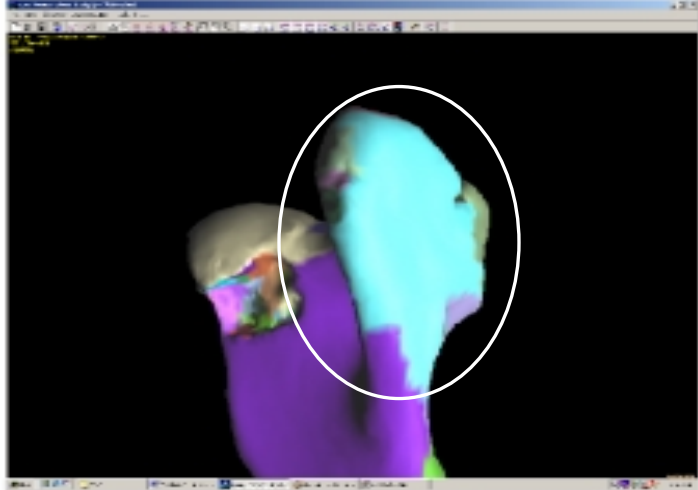
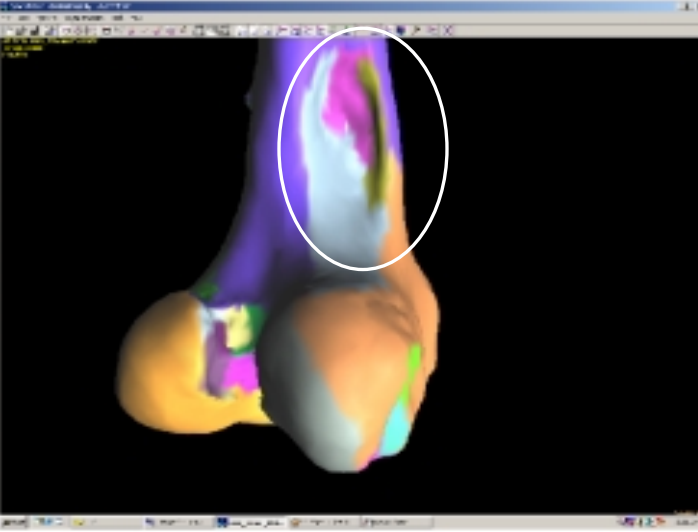
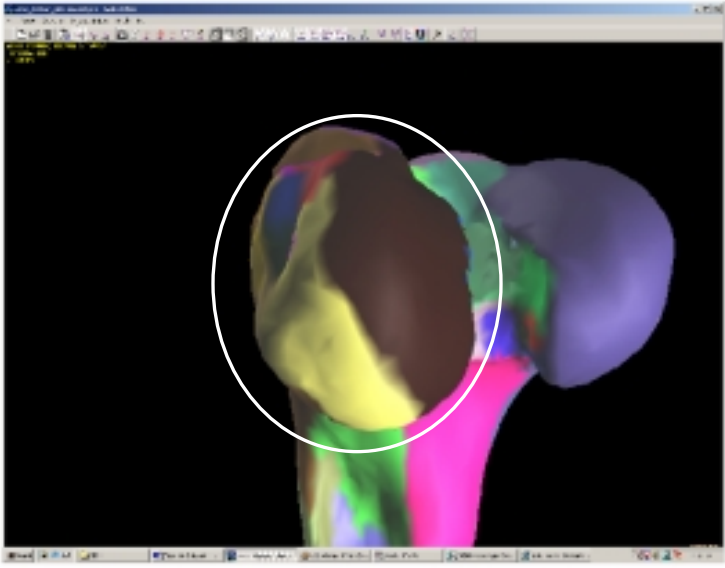
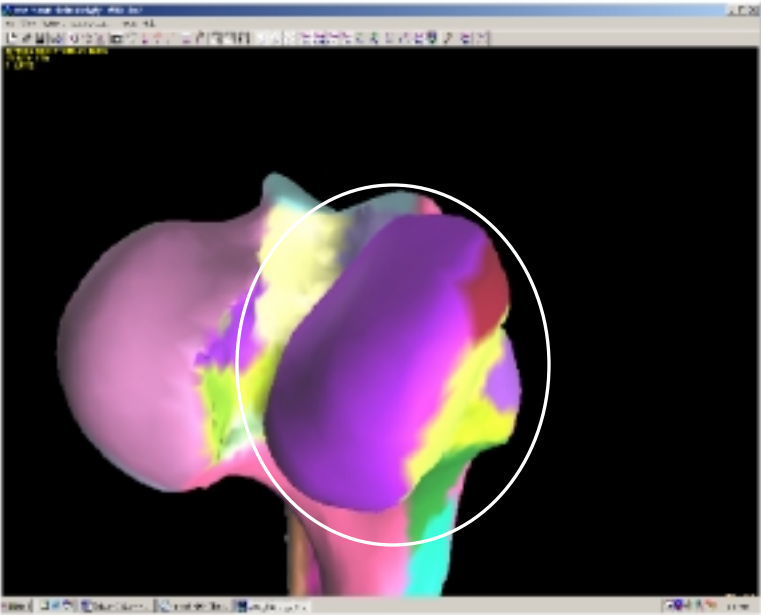
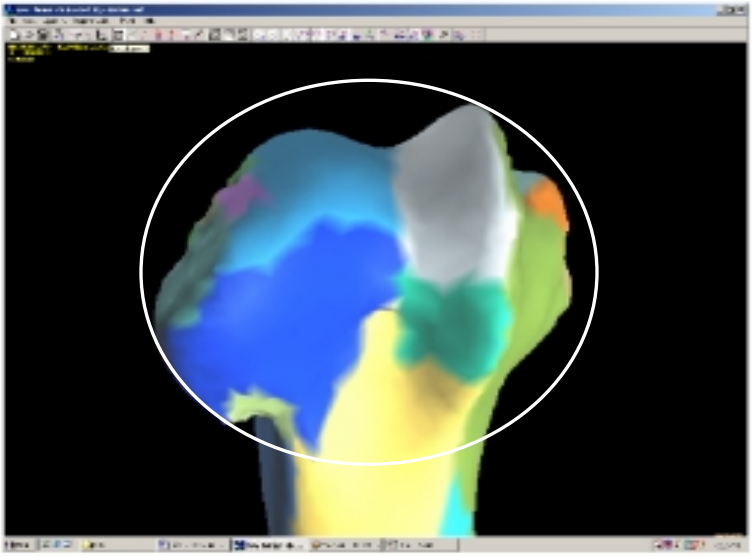
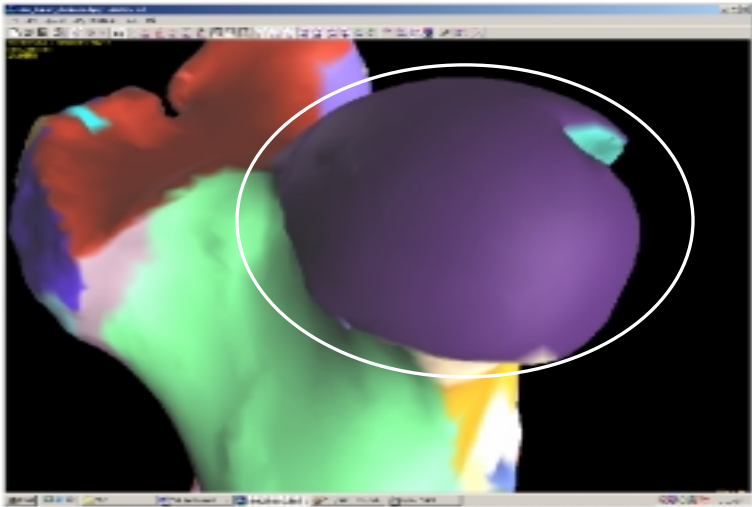


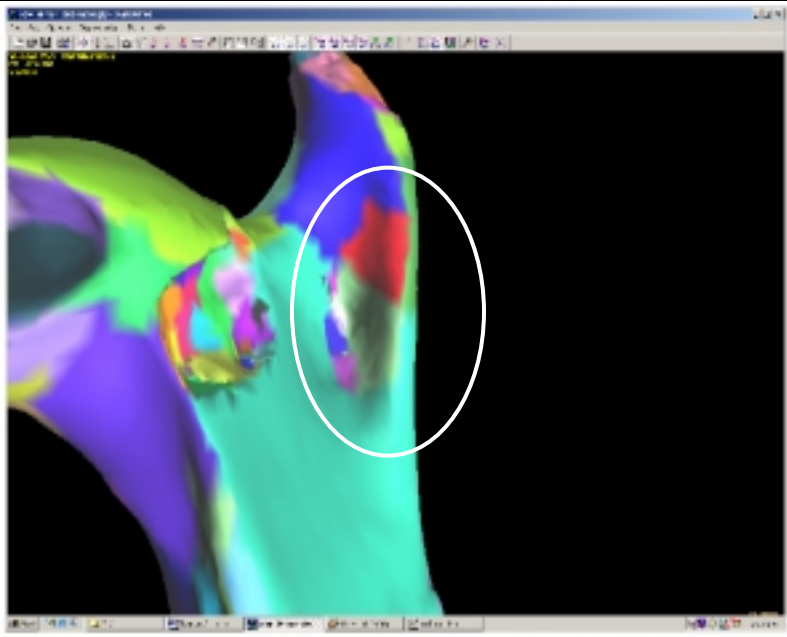
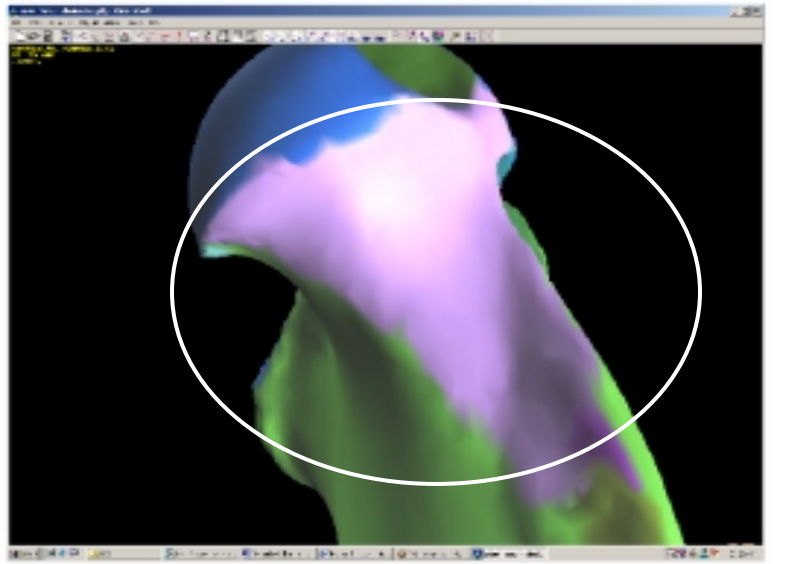
Figure A2.4: Head [22]

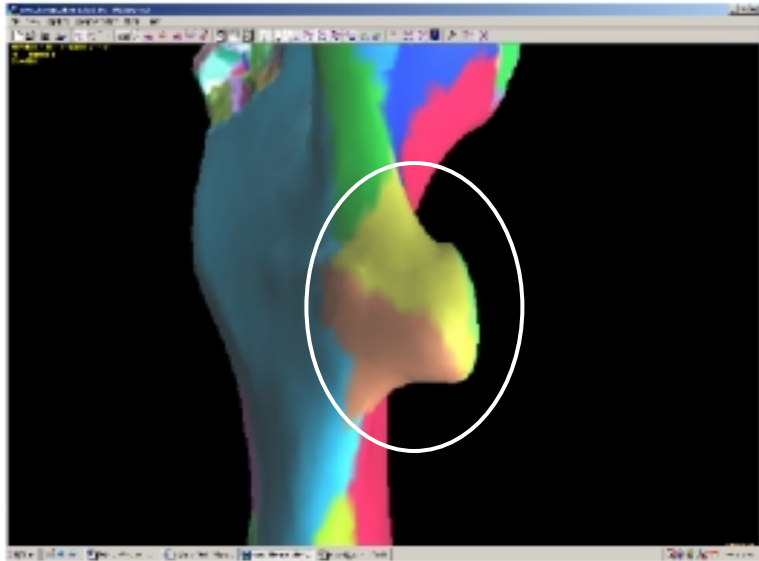
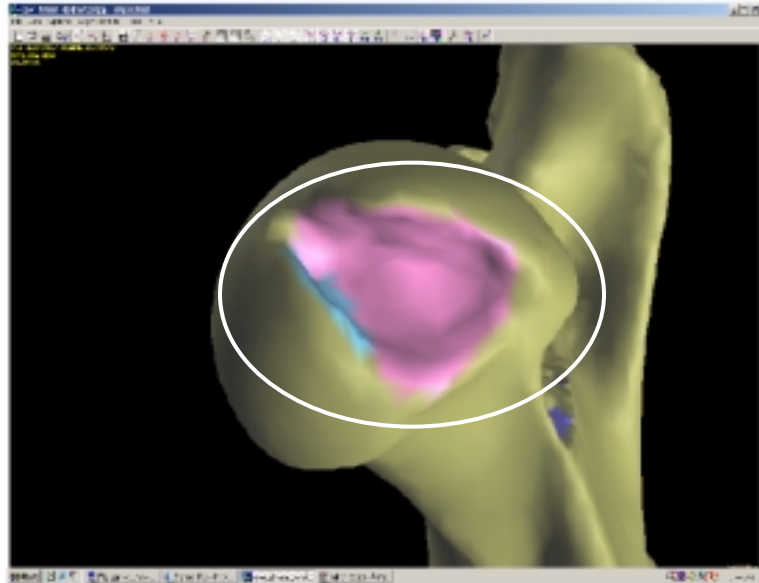
APPENDIX III
FEATURE EXTRACTION OF THE FEMUR USING WATERSHED
FOR MULTIPLE THRESHOLD VALUES

S. No.	FEATURE	THRESHOLD VALUE	SNAPSHOT	COMMENTS
1.	MAJOR TROCHANTER	0.09166 - 0.120804		The watershed is able to pick up the feature at the mentioned threshold range, but indicates a few small patches at the top of the trochanter. This can be due to the roughness in the bone caused by wear and tear. Some of these patches do merge with an increase in the threshold value.
2.	SUPRACONDYLOID FOSSA	0.13263 – 0.21104		This feature seems to be quite difficult for the Watershed to pick up. It detects the feature as three distinct patches over the range of values indicated.

3.	LATERAL CONDYLE	0.15804 - 0.17754		<p>The Lateral Condyle is one of the surfaces of the femur that matches onto the Tibia. The lateral condyle has been split up into two surfaces of almost equal size. The break occurs at the line of inflexion in the curvature.</p>
4.	MEDIAL CONDYL	0.14029 – 0.19947		<p>This is the other surface that matches onto the Tibia. This has been almost completely picked up by the algorithm. This may be due to the smooth and continuous curvature of this surface.</p>

5.	TROCHLEA	0.08836 - 0.13416		<p>The trochlea can be at best be detected as four distinct surfaces. These four surfaces remain the same over the range of values indicated.</p>
6.	HEAD	0.14945 – 0.19990		<p>The upper surface of the head is picked up by watershed very well. The threshold value range clearly demarcates the head from the other features.</p>

7.	TROCHANTERIC FOSSA	0.11301 - 0.12246		<p>The Trochanteric Fossa is almost impossible to pick up as it consists of many small curvatures. There is a collection of patches that denote this feature. These patches remain constant in the range given.</p>
8.	NECK	0.26127 - 0.27894		<p>The entire neck has been picked up as one feature for the given range of threshold values. This is one of the very few features that have been highlighted as one single patch.</p>

9.	MINOR TROCHANTER	0.05331 - 0.05907		<p>The Minor Trochanter is a feature jutting out of the bone. It has been split into four patches. The sharp inflexion causes the watershed to pick the feature as separate curvatures.</p>
10.	FOVEA CAPITUS	0.55007 – 0.64441		<p>The fovea capitis is distinctly picked up by watershed as two patches. One of the patches is much smaller in size (Blue) compared to the other. The range of values for this feature is pretty large compared to most of the other features.</p>